

Constraints on spin-dependent parton distributions at large x from global QCD analysis

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Abstract

We investigate the behavior of spin-dependent parton distribution functions (PDFs) at large parton momentum fractions x in the context of global QCD analysis. We explore the constraints from existing deep-inelastic scattering data, and from theoretical expectations for the leading $x \rightarrow 1$ behavior based on hard gluon exchange in perturbative QCD. Systematic uncertainties from the dependence of the PDFs on the choice of parametrization are studied by considering functional forms motivated by orbital angular momentum arguments. Finally, we quantify the reduction in the PDF uncertainties that may be expected from future high- x data from Jefferson Lab at 12 GeV.

I. INTRODUCTION

Recently a new global next-to-leading order (NLO) analysis [1] of spin-dependent parton distribution functions (PDFs) was performed by the JAM (Jefferson Lab Angular Momentum) Collaboration [2], in which particular attention was paid to the valence quark-dominated region at high parton momentum fractions x and low four-momentum transfers Q^2 . This region requires careful treatment of the potentially important $1/Q^2$ power corrections associated with target mass and higher twist contributions to the inelastic cross sections, as well as nuclear smearing effects when using deuterium and ^3He data. The analysis [1] indeed found significant effects on the polarized leading twist PDFs when twist-3 and twist-4 power corrections in both the spin-dependent g_1 and g_2 structure functions were taken into account. In particular, the Δd^+ distribution (defined as $\Delta d^+ \equiv \Delta d + \Delta \bar{d}$) was found to have a significantly larger magnitude at $x \gtrsim 0.2$ than in previous global analyses, driven partly by a large and positive twist-4 correction to the neutron g_1 structure function.

Analyses such as those in Ref. [1] that systematically incorporate subleading effects in an effort to accommodate data over a broad range of kinematics can therefore provide a more solid basis for extracting reliable information on PDFs and their uncertainties, especially in regions such as at large x where data are relatively scarce [3]. In fact, the absence of high-precision polarization data at high x , particularly for the neutron (or ^3He), has meant that spin-dependent PDFs are essentially unconstrained for $x \gtrsim 0.5 - 0.6$. This is rather unfortunate, given that polarized PDFs, and ratios of polarized to unpolarized PDFs, are quite sensitive to the details of nonperturbative quark-gluon dynamics in the nucleon at high x , with theoretical predictions differing in some cases even in sign [4].

In the simplest quark models, for example, spin-flavor symmetry implies constant ratios of PDFs, $\Delta u/u = 2/3$, $\Delta d/d = -1/3$ and $\Delta d/\Delta u = -4$. Symmetry breaking effects, which typically generate a larger energy for axial vector spectator diquark configurations compared to scalar diquarks, generally raise the $\Delta u/u$ ratio to unity in the $x \rightarrow 1$ limit, while keeping $\Delta d/d$ unchanged from the SU(6) value [5–8]. Calculations of one-gluon exchange in perturbative QCD (pQCD), on the other hand, predict that [9]

$$\frac{\Delta q(x)}{q(x)} \rightarrow 1 \quad \text{as } x \rightarrow 1, \quad (1)$$

where $q(x)$ is the spin-averaged distribution, for all quark flavors q . Similar expectations arise also from arguments based on local quark-hadron duality [10–13].

While most global PDF analyses do not include conditions such as in Eq. (1) in order to avoid introducing theoretical bias into the PDF extraction, Brodsky, Burkardt and Schmidt [14] proposed a simple parametrization of PDFs in which the large- x constraints of Eq. (1) were built in. Only a limited set of data was analysed in Ref. [14], however, although a subsequent global analysis utilizing the pQCD expectations was performed by Leader, Sidorov and Stamenov (LSS) [15]. This found that a reasonably good fit to the available data was indeed possible, with the feature of a steep rise in the $\Delta d/d$ ratio at intermediate values of x . Later high-precision data from the E99-117 experimental at Jefferson Lab [16] observed the first evidence of a turn over in the A_1^n neutron polarization asymmetry from negative to positive values, although at somewhat larger values of x ($x \sim 0.5 - 0.6$) than those in the fit of Ref. [15].

In a more recent analysis, Avakian *et al.* [17] showed that inclusion of $L_z = 1$ components in the lowest three-quark Fock state of the nucleon, in addition to the usual $L_z = 0$ configurations, can generate additional terms that behave as $(1 - x)^5 \log^2(1 - x)$ at large x , which can play an important role numerically. Generalizing the pQCD-inspired parametrization from Ref. [14] to include the subleading $\log^2(1 - x)$ terms, Avakian *et al.* showed that the large- x asymmetry data could be well fitted while preserving the asymptotic constraints of Eq. (1). In particular, the new $\Delta d/d$ ratio was found to remain negative until $x \approx 0.75$, as suggested by the E99-117 data [16], before rising towards unity at higher x values.

While the analysis of Ref. [17] showed the potential of high- x data to reveal information about the orbital angular momentum (OAM) of quarks in the nucleon, it was not based on a comprehensive global analysis of all available data. The goal of the present work is to examine the behavior of spin-dependent PDFs in the $x \sim 1$ region in the context of a global QCD analysis, including the effects of the $x \rightarrow 1$ constraints in Eq. (1) and of the $\log^2(1 - x)$ terms inspired by pQCD.

We begin our discussion in Sec. II by summarizing the recent global analysis [1] from the JAM Collaboration, which we use as the baseline fit for our large- x studies. To explore the dependence on the choice of parametrization and allow for more direct connection with quark orbital angular momentum, we also consider a simplified functional form which uses a smaller number of parameters. The effects on the fits of additional terms in the PDF parametrizations induced by nonzero orbital angular momentum are investigated, together with the impact on the Δu and Δd PDFs from imposing constraints for the $x \rightarrow 1$ behavior

from perturbative QCD. In Sec. III we repeat the global analysis using in addition pseudodata generated at the kinematics of future data from several experiments planned at the 12 GeV energy upgraded Jefferson Lab, and quantify the resulting reduction in the PDF errors at high x . Finally in Sec. IV we draw some conclusions of the present analysis and outline steps for future work.

II. PARTON DISTRIBUTIONS AT LARGE x

For our exploration of the large- x region we use as a baseline the PDFs from the JAM analysis in Ref. [1]. The JAM PDFs were obtained from a global NLO fit to all available data on inclusive polarized deep-inelastic scattering asymmetries for $Q^2 > Q_0^2 = 1 \text{ GeV}^2$ and $W > 1.87 \text{ GeV}$. Inclusion of low- Q^2 and low- W data necessitated a careful treatment of the subleading $1/Q^2$ contributions, to both the g_1 and g_2 structure functions, from target mass and higher twist corrections, as well as nuclear smearing effects for deuterium and ^3He data. By fitting directly the longitudinal and transverse polarization asymmetries, where available, one avoids introducing biases that would otherwise arise in fits to the spin-dependent structure functions, which are often extracted from the experimental asymmetries under different assumptions for the spin-averaged structure functions.

A standard parametrization was used for the polarized quark, antiquark and gluon distributions in terms of four parameters plus an overall normalization,

$$x\Delta q^+(x, Q_0^2) = N x^\alpha (1-x)^\beta (1 + \epsilon\sqrt{x} + \eta x), \quad (2)$$

where $\Delta q^+ \equiv \Delta q + \Delta \bar{q}$, at the input scale Q_0^2 . At large values of x the antiquark and gluon PDFs play a negligible role, so that the inclusive DIS data alone are sufficient to determine the Δu^+ and Δd^+ distributions individually. A total of over 1,000 data points were used in the analysis, giving an overall χ^2 per data point of 0.98 (see Table I). The resulting Δu^+ and Δd^+ distributions are illustrated in Fig. 1, together with the ratios to the spin-averaged PDFs, $\Delta u^+/u^+$ and $\Delta d^+/d^+$, at $Q^2 = 1 \text{ GeV}^2$.

Unlike the Q^2 dependence of PDFs, which is determined by the Q^2 evolution equations to a given order in the strong coupling α_s [18], the x dependence of PDFs is generally not accessible directly from pQCD calculations. An exception is the kinematic region at large x , where hard gluon exchange between the quarks in the leading three-quark Fock state

TABLE I: χ^2 values per number of data points N_{dat} for the various fits discussed in this analysis, including the JAM, SIMP and OAM fits, with or without the $x \rightarrow 1$ constraint in Eq. (1), and including leading twist (LT) contributions only. For the JAM fit we also considered the cases where the Δd^+ PDF was forced to cross zero at $x = 0.5$ and $x = 0.75$.

χ^2/N_{dat}	JAM	OAM	SIMP	JAM(LT)	OAM(LT)	SIMP(LT)
no $x \rightarrow 1$ constraint	0.98	0.98	1.02	1.07	1.09	1.12
with $x \rightarrow 1$ constraint	1.01	1.02	—	1.11	1.16	—
Δd^+ crossing at $x = 0.75$	1.02	—	—	—	—	—
Δd^+ crossing at $x = 0.5$	1.06	—	—	—	—	—

component of the nucleon can be used to determine the dominant contributions to the x dependence of the PDFs in the $x \rightarrow 1$ limit [9]. Typically one finds that the quark PDFs in the nucleon behave as $\sim (1-x)^{2n_s-1}$, where n_s is the minimum number of partons that are spectators to the hard collision [9, 14], so that for $n_s = 2$ the leading exponent is equal to 3. More generally, the exponent on $(1-x)$ also depends logarithmically on Q^2 [19], although the scale from which this should evolve is *a priori* unknown. Nevertheless, global PDF fits do find parameters β in Eq. (2) that are close to the pQCD (or quark “counting rule”) predictions; for the JAM fit, for instance, one has $\beta_u = 3.3$ and $\beta_d = 4.0$ for Δu^+ and Δd^+ , respectively, at the input scale Q_0^2 .

Of course, the additional polynomial terms in (2) with coefficients ϵ and η obscure the direct connection between the x dependence of the fitted distributions and the predicted pQCD behavior. To make the connection more explicit, we consider a fit based on a simplified functional form, with parameters ϵ and η in Eq. (2) set to zero. The resulting fit, labeled “SIMP” in Fig. 1, gives similar Δu^+ and Δd^+ distributions to those from the full JAM analysis, albeit with a slightly larger overall χ^2 value. The leading $(1-x)$ exponents in this case are reduced slightly to $\beta_u = 2.5$ and $\beta_d = 3.4$.

As well as specifying the leading $x \rightarrow 1$ behavior of the PDFs, the pQCD counting rules also predict that the dominant contribution to the cross section, in a reference frame where the nucleon is moving fast along the z -axis, is from scattering off quarks with the *same* helicity as that of the nucleon. This implies that asymptotically the helicity-aligned distributions

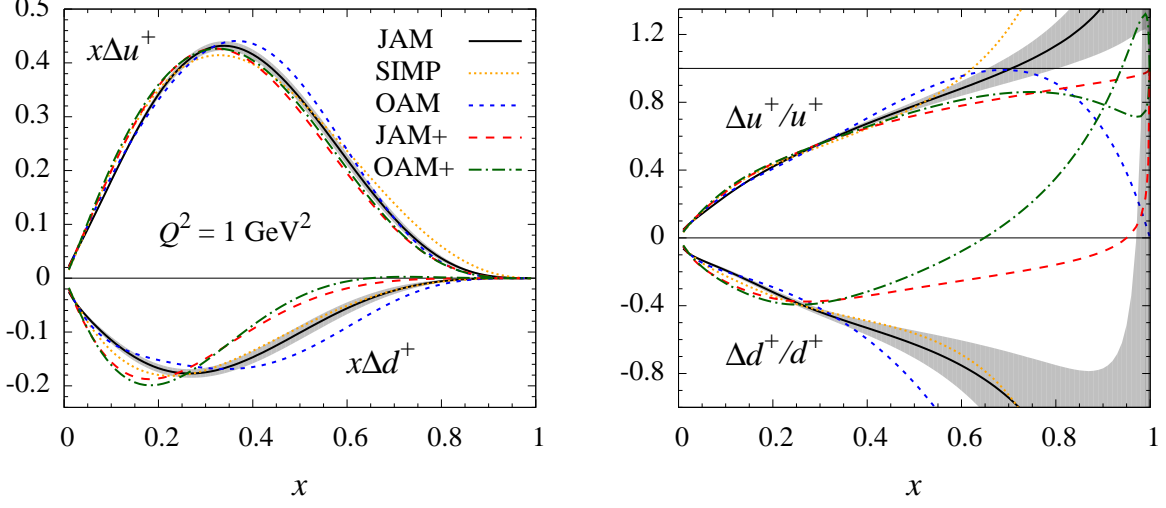


FIG. 1: Spin-dependent parton distributions Δu^+ and Δd^+ (**left**) and their ratios $\Delta u^+/u^+$ and $\Delta d^+/d^+$ to the spin-averaged distributions (**right**) at a scale of $Q^2 = 1 \text{ GeV}^2$. The distributions from the JAM analysis [1] (black solid curves) are compared with those using a more basic parametrization (orange dotted curves), the “OAM” parametrization inspired by nonzero orbital angular momentum considerations (blue short-dashed curve), and the “JAM+” (red long-dashed curves) and “OAM+” (green dot-dashed curves) fits which include the $x \rightarrow 1$ constraint from Eq. (1).

dominate both the unpolarized and polarized PDFs, so that the ratio $\Delta q^+/q^+ \rightarrow 1$ as $x \rightarrow 1$ for all quark flavors q , as in Eq. (1). In this scenario the A_1 polarization asymmetries in DIS are therefore expected to approach unity for both the proton and neutron.

Unfortunately, current data cannot definitively confirm the pQCD expectations. While the proton A_1^p asymmetries, which have been measured to $x \approx 0.7$ in the DIS region, are consistent with an approach towards unity in the $x \rightarrow 1$ limit, the neutron (or ^3He) data extend only to $x \approx 0.6$ and are generally consistent with a zero or negative asymmetry. The dearth of high- x data means that the spin-dependent PDFs, and particularly the Δd^+ distributions, are essentially unconstrained above this region. Consequently the spin-dependent PDFs obtained from global analyses often violate the positivity condition $|\Delta q(x)| \leq q(x)$ at large x (although strictly speaking these need not be satisfied beyond leading order). This can be seen in Fig. 1 for both the JAM and SIMP (and other) fits, and in general will be a feature of any global fit which does not *a priori* impose the positivity constraint (or else

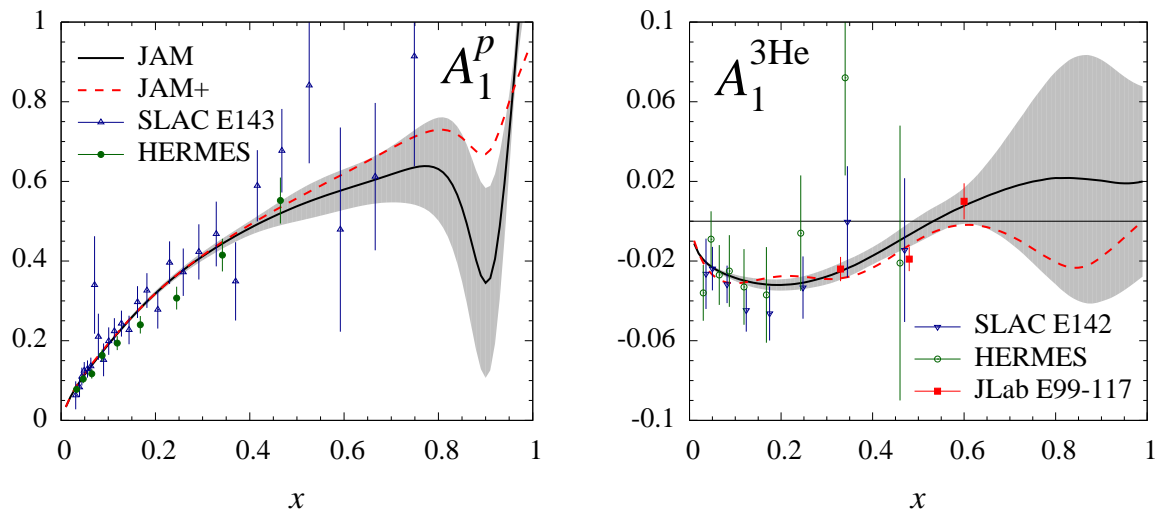


FIG. 2: Comparison of JAM (black solid curves and gray band) and JAM+ (red dashed curves) fits at $Q^2 = 3 \text{ GeV}^2$ with proton (**left**) and ^3He (**right**) A_1 polarization asymmetry data for similar Q^2 values. The proton data are from the SLAC E143 [22] and HERMES [23] experiments, while the ^3He data are from the SLAC E142 [24], HERMES [25] and Jefferson Lab E99-117 [16] experiments.

fit the individual helicity-aligned and helicity-antialigned distributions separately). Note that in the present work the unpolarized fits are based on the recent NLO global analysis from Ref. [20]. Ideally one should perform a global fit of polarized and unpolarized data simultaneously and extract the helicity-aligned and antialigned distributions. This will be particularly important in future analyses that include semi-inclusive data sets, where transverse momentum distributions, which are expected to be different for different helicity states [21], will play a more important role.

To explore the effect of the $x \rightarrow 1$ constraints (1) on PDFs in the context of the JAM global analysis, we consider a modified fit in which the $\Delta u^+/u^+$ and $\Delta d^+/d^+$ ratios are both forced to unity at $x = 1$. The resulting fit, denoted by “JAM+” in Fig. 1 and Table I, shows that one can indeed obtain a reasonable description of data, consistent with the pQCD $x \rightarrow 1$ limit, with an overall $\chi^2/N_{\text{dat}} = 1.01$ that is only slightly larger than for the unconstrained fit. This is confirmed also in Fig. 2, where the JAM and JAM+ fits are compared with data on the A_1 asymmetries for the proton and ^3He from SLAC, HERMES, and Jefferson Lab. The increase in χ^2 is associated with the reduced magnitude of Δd^+ in the intermediate- x

region, $x \gtrsim 0.3$, which in order to maintain the normalizations required by the triplet and octet axial vector charges [1], becomes slightly more negative (with larger magnitude) at smaller x , $x \lesssim 0.2$, where considerably more data exist. The Δu^+ distribution, on the other hand, which was already large and positive in the JAM fit, undergoes relatively little change with the $x = 1$ constraint. Note that the constraint (1) cannot be accommodated by the SIMP parametrization, as without nonzero ϵ or η terms in Eq. (2) the Δd^+ distribution cannot change sign at any x .

Interestingly, the turn-over in Δd^+ from negative to positive values occurs at relatively large values of x , $x \approx 0.95$, which would be challenging to observe experimentally. This is significantly higher than the turn-over found in the earlier LSS analysis [15] at $x \sim 0.5$, which was subsequently found to be in conflict with the neutron asymmetry data from the E99-117 experiment at Jefferson Lab [16]. Indeed, the existing data tend to disfavor fits with positive d quark polarization over the measured x range. We studied this by forcing a zero crossing in Δd^+ at $x = x_0$, with the distribution becoming positive for $x > x_0$. For the JAM fit with $x_0 = 0.75$ the χ^2/N_{dat} increased slightly compared to the JAM+ fit, but the increase was significantly greater, to $\chi^2/N_{\text{dat}} = 1.06$, when the crossing was set at a lower value, $x_0 = 0.5$.

Of course, the behavior of leading twist PDFs at large x is also influenced to some extent by the effect of higher twist corrections, which become more important as $x \rightarrow 1$. Using either the JAM or SIMP parametrizations *without* including the $1/Q^2$ corrections generally results in a significantly worse fit, with χ^2/N_{dat} values increasing from ≈ 1 to ≈ 1.1 in Table I, regardless of whether the constraint (1) is imposed or not. This supports the findings of Ref. [1] that the Q^2 dependence of the data over the range considered here cannot be accommodated by the parametric form in Eq. (2) with Q^2 corrections from Q^2 evolution only.

To address the problem of the rapid rise of Δd^+ at too low values of x , Avakian *et al.* [17] generalized the pQCD calculations for the $x \rightarrow 1$ behavior of PDFs by considering components of the lowest three-quark Fock-state wave function with nonzero orbital angular momentum, $L_z = 1$, in addition to the usual $L_z = 0$ configurations. The $L_z = 1$ contributions were found to generate additional terms that behave as $\sim (1-x)^5 \log^2(1-x)$ at large x . Although formally subleading in the $x \rightarrow 1$ limit compared with the dominant $\sim (1-x)^3$ contributions expected from the $L_z = 0$ component, numerically the log terms can play

an important role. In particular, Avakian *et al.* found that by using the pQCD-inspired parametrization from Ref. [14] supplemented by the subleading $\log^2(1-x)$ terms, the large- x asymmetry data could be well fitted while preserving the asymptotic constraints of Eq. (1). Furthermore, the resulting $\Delta d^+/d^+$ ratio remained negative until $x \approx 0.75$, as suggested by the E99-117 data [16], before rising towards unity at higher x values.

To explore the importance of the additional $\log^2(1-x)$ terms in the context of a global QCD analysis of all data, at small and high x , we use as a basis the simplified parametrization with $\epsilon = 0 = \eta$ in Eq. (2), together with the log term inspired by the OAM arguments,

$$x\Delta q^+ = N x^\alpha (1-x)^\beta + N' x^{\alpha'} (1-x)^{\beta'} \log^2(1-x). \quad (3)$$

with arbitrary relative normalization N' . It is reasonable as a first approximation to assume that the $x \rightarrow 0$ behavior of the OAM-inspired term is the same as the standard term, $\alpha' = \alpha$. To reduce the number of parameters that can be reliably determined from the existing data, we also fix $\beta' = 5$ in accordance with the pQCD derivation [17], even though the corresponding power of $(1-x)$ in the first term of Eq. (3) remains a free parameter.

The resulting fit, denoted by “OAM” in Fig. 1, is of comparable quality to the JAM fit ($\chi^2/N_{\text{dat}} = 0.98$), with similar Δu^+ and Δd^+ distributions at moderate $x \lesssim 0.4$, but differing at higher x values, where there are no constraints from data. If one includes in addition the $x = 1$ constraint from Eq. (1), the effect on the new constrained fit, labelled “OAM+” in Fig. 1, is again similar to that on the JAM+ fit. Namely, the Δd^+ PDF is forced to become positive at $x \approx 0.65$, and the reduced magnitude forces the distribution at smaller x values to become more negative in order to preserve the sum rules. The Δu^+ distribution remains relatively unchanged, and the overall $\chi^2/N_{\text{dat}} = 1.02$ is comparable to that for JAM+. The OAM and OAM+ fits with LT contributions only are once again considerably worse than the full fits including higher twist effects, indicating that the need for subleading corrections is independent of the parametric form chosen for the LT component.

The results of the above fits suggest that with the additional flexibility afforded by the $\log^2(1-x)$ terms in Eq. (3), the current data certainly *can* be accommodated with the OAM-inspired parametrization. On the other hand, the JAM and JAM+ fits based on the standard parametrization in Eq. (2) give perfectly good descriptions of the available data over the entire range of kinematics, and *do not need* the introduction of the additional log terms. The constraint from Eq. (1), when imposed on the standard PDFs, can be satisfied

without substantially modifying the distributions in the regions constrained by data. One should also caution, however, that the $\log^2(1-x)$ term in the OAM-inspired parametrization (3) cannot at present be directly related to the component of the nucleon's spin carried by the quark orbital angular momentum [26]. Its appearance in the present analysis serves more to illustrate the possible role played by OAM in understanding PDFs at large x , and to explore the systematic uncertainties that may arise from different assumptions about the functional forms used for the PDF parametrizations. Fits including only terms with $L_z = 0$ and $L_z = 1$ [17], which can be interpreted in terms of relative contributions from different orbital states, will be reported elsewhere [27].

A scenario in which one finds qualitatively different fits with comparable χ^2 values, or fits which differ by amounts that are larger than the uncertainties from the propagation of experimental errors, indicates a lack of information at large x , and an underestimate of the systematic errors in this region. In the absence of clearer theoretical constraints at $x \lesssim 1$, the problem can be best addressed of course by the availability of new data at higher x values than are currently available, which we discuss in the next section.

III. CONSTRAINTS FROM FUTURE DATA

Constraining the behavior of the polarization asymmetries A_1 , and consequently of the spin-dependent PDFs, in the limit as $x \rightarrow 1$ is one of the featured goals of the experimental physics program planned for the 12 GeV energy upgraded CEBAF accelerator at Jefferson Lab. Data from several experiments are expected to be collected for values of x as high as ≈ 0.8 for DIS kinematics [28], and even higher x in the nucleon resonance region. This should significantly reduce the PDF uncertainties for $x \gtrsim 0.5$, especially for the Δd^+ distribution, which will be more strongly constrained by new data on the ^3He asymmetry.

To estimate the possible impact of the new Jefferson Lab data we use the projected statistical and systematic uncertainties for the proposed experiments at the x and Q^2 values where the asymmetries will be measured [28]. The pseudodata are generated by randomly distributing the central values of the points around the JAM fit in Fig. 2 for hydrogen, deuterium and ^3He targets (distributing them around any of the other fits considered in this analysis would be equally suitable). The reduction in the PDF uncertainties, illustrated in Fig. 3, is significant, with the relative error on Δu^+ and Δd^+ decreasing by $\sim 70\%$ for

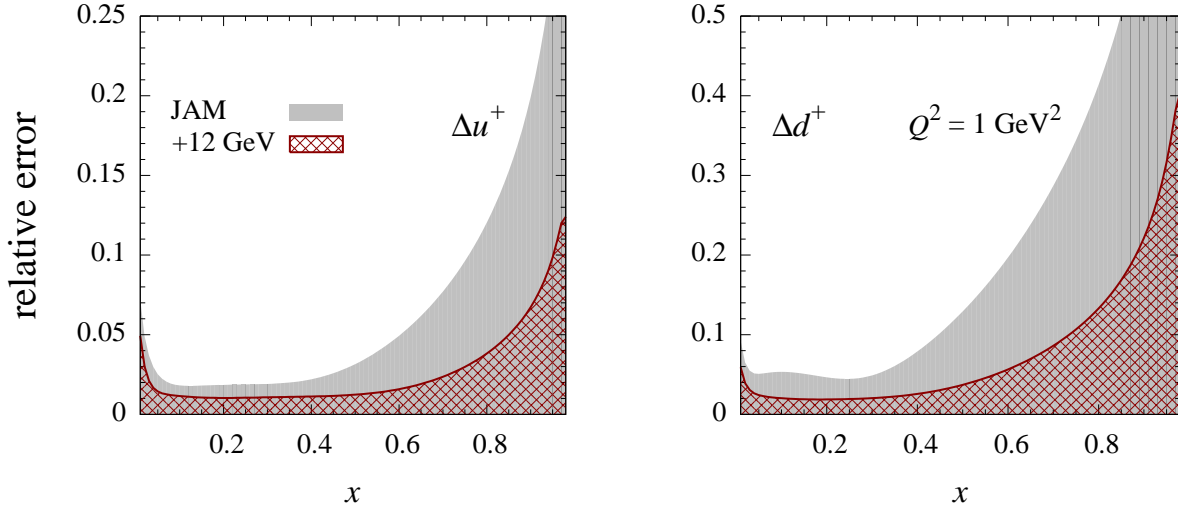


FIG. 3: Relative error on the Δu^+ (left) and Δd^+ (right) PDFs for the JAM fit at $Q^2 = 1 \text{ GeV}^2$ (gray band) and for JAM including pseudodata expected from planned Jefferson Lab 12 GeV experiments [28] (red hashed area).

$x = 0.6 - 0.8$ at the input scale $Q^2 = 1 \text{ GeV}^2$.

Reductions in the spin-dependent PDF errors such as these, combined with similarly dramatic reductions expected for the uncertainty on the unpolarized d quark distribution (or the d/u ratio) [29], should at the very least allow one to discriminate between a $\Delta d/d$ ratio that remains negative, as in simple quark models, and one that approaches ~ 1 in the $x \rightarrow 1$ limit, as predicted by pQCD arguments. Beyond this there may be additional constraints on the $x \rightarrow 1$ behavior of spin-dependent PDFs from an electron-ion collider [30–32], particularly if the spectator tagging technique [33] in semi-inclusive DIS from the deuteron or ^3He can be extended to polarized beams and targets.

IV. CONCLUSIONS

The aim of this analysis was to investigate whether existing data from polarized lepton–nucleon DIS is able to provide any constraints on the $x \rightarrow 1$ behavior of spin-dependent PDFs in the context of a global QCD analysis. Using the recent JAM fit as a baseline, we showed that demanding the polarized to unpolarized PDF ratios $\Delta q^+/q^+$ to approach unity at $x = 1$ results in equally good fits to the available data, even though the resulting changes to the Δd^+ PDF are significant in the intermediate- x region. With dramatically different

behaviors for the $\Delta d^+/d^+$ ratio allowed for $x \gtrsim 0.3$, this highlights the critical need for precise data sensitive to the d quark polarization at large x values.

We have investigated the recent suggestion that inclusion of Fock states in the nucleon wave function with nonzero orbital angular momentum gives rise to additional contributions to PDFs proportional to $(1-x)^5 \log^2(1-x)$ [17] which could play an important role numerically. Employing an extension of the typical functional form used in standard PDF analyses which allows for the log dependence, we find that the generalized parametrization is also able to provide a good description of the existing DIS data, with or without the $x = 1$ constraint. While there has been a first indication of a rise above unity of the neutron (^3He) polarization asymmetry for $x \gtrsim 0.6$ [16], the data still generally prefer a negative Δd^+ distribution at large x even with the $x = 1$ limit built in, although the cross over to positive values depends on the parametrization chosen (at ≈ 0.95 for the JAM+ and ≈ 0.65 for OAM+).

Further progress on this problem is expected soon with new data expected from several experiments at the 12 GeV energy upgraded Jefferson Lab, which aim to measure polarization asymmetries of protons, deuterons and ^3He up to $x \sim 0.8$ in DIS kinematics [28]. Using the projected statistical and systematic errors from these experiments, we explored the possible impact on the PDFs and their uncertainties in this region. We find reductions in both the Δu^+ and Δd^+ PDFs of up to $\approx 70\%$ for $x \approx 0.6 - 0.8$ in the JAM fit, with significant reductions also at smaller x values. This should considerably narrow the range of possible asymptotic $x \rightarrow 1$ behaviors of the $\Delta q^+/q^+$ ratios, and for the first time provide critical tests of the various theoretical scenarios that have been proposed to describe PDFs in the large- x region [4-9, 14].

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